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Indian Standard

GUIDE FOR THE USE OF QUARTZ CRYSTAL UNITS FOR FREQUENCY CONTROL AND SELECTION

(First Revision)

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Indian Standard

GUIDE FOR THE USE OF QUARTZ CRYSTAL UNITS FOR FREQUENCY CONTROL AND SELECTION

(First Revision)

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Indian Standard

GUIDE FOR THE USE OF QUARTZ CRYSTAL UNITS FOR FREQUENCY CONTROL AND SELECTION

(First Revision)

0. FOREWORD

0.1 This Indian Standard (First Revision) was adopted by the Indian Standards Institution on 16 September 1980, after the draft finalized by the Piezoelectric Devices for Frequency Control and Selection Sectional Committee had been approved by Electronics and Telecommunication Division Council.

0.2 This standard was originally published in 1964, largely based on IEC Pub 122-2 : 1962 'Quartz crystal units for oscillators, Section Three Guide to the use of quartz oscillator crystals', and covered guidelines for the use of quartz crystal units for oscillators. Taking into account the developments taking place on the international level and to include guidelines for the use of quartz crystal units for filters also, the revision has been undertaken.

0.3 This standard has been prepared to serve as a guide to both user and manufacturer for the use of quartz, crystals for filters and oscillators so that the crystal units may be used to their best advantage.

0.3.1 This standard draws attention to some of the more fundamental questions which should be considered by the user before he places his order for a unit for a new application, and in so doing will, it is hoped, help ensure against unsatisfactory performance, unfavourable cost and availability. However, it is not intended to explain theory and not to attempt to cover all the eventualities that may arise in practical circumstances. Lastly, it should not be considered as a substitute for close liaison between users and manufacturers.

0.4 It may not be possible to achieve certain combinations of the characteristics of crystals considered in this standard. Reference and use should, therefore, be made of relevant specifications, as well as manufacturers data sheets and recommendations. In particular cases it shall be desirable to leave the exact design of a crystal unit largely to the manufacturer who shall endeavour to meet the user's requirements in a practical way.

0.4.1 The detail specifications are expected to include wide range of crystal units with a standardized performance and dimensions, and the user should, wherever possible, select crystal units from these detail specifications, even if it may lead to minor modifications to the circuit in order that standard units are used. The multiplicity of types varying only in a small degree is uneconomical and restricts interchangeability.

0.5 While preparing this standard, assistance has been derived from the following publications issued by the International Electrotechnical Commission :

> IEC Pub. 122-2 : 1962 'Quartz crystal units for oscillators, Section Three : Guide to the use of quartz oscillator crystals ' including Amendment No. 1.
>
> Doc 49 (Sectt) 121 ' Guide to the use of quartz crystal units for frequency control and selection '.

1. SCOPE

1.1 This standard gives guidance for the use of quartz crystal units for frequency control and selection, that is, oscillator and filter applications.

2. TERMINOLOGY

2.1 For the purpose of this standard, definitions covered in IS : 1885 (Part XLIV) - 1978* shall apply.

3. QUARTZ CRYSTAL AS AN ELECTRONIC COMPONENT

3.1 *General* — The quartz crystal element is a vibrating resonant plate whose orientation and dimensions will determine its frequency and which relies on the piezoelectric effect to couple it to an electrical circuit. The intrinsic properties of quartz make it a unique simple device for highly accurate and stable frequency control and selection because of its high 'quality factor'. Crystals are not a primary frequency standard, but when precisely defined may provide stabilization far in excess of most requirements in the electronic industry.

The quartz crystal element is cut from monocrystalline quartz with precise orientation to the crystalographic axes as shown in Fig. 1.

NOTE — This illustration shows only generalized examples of the most commonly used crystal cuts.

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*Electrotechnical vocabulary : Part XLIV Piezoelectric devices.

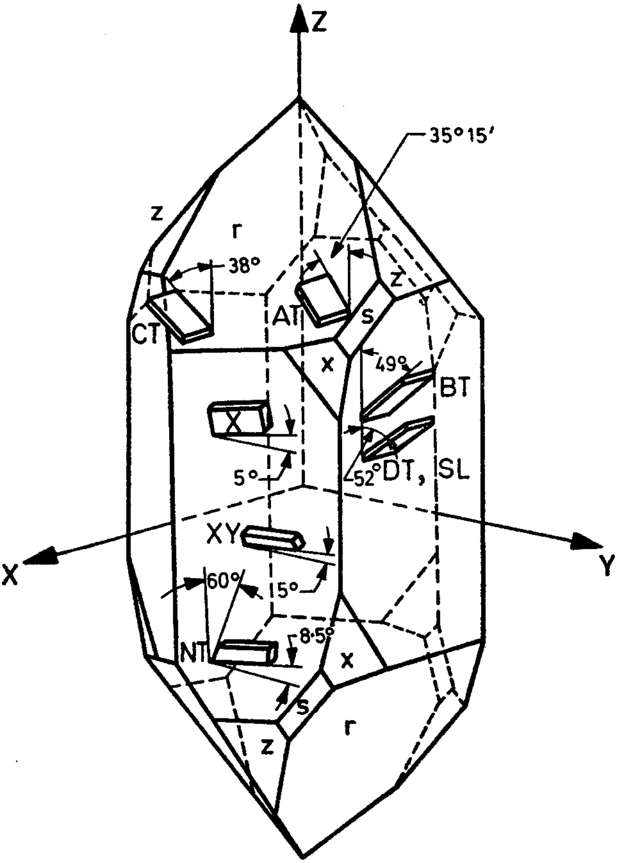


Fig. 1 Designation of The Most Commonly Used Crystal Cuts

This figure shows a block of natural quartz crystal. However, most manufacturers now use synthetic material. Techniques have advanced to a point where synthetic quartz is almost indistinguishable from natural material with regard to electrical performance.

Note — In this guide the use of synthetic quartz crystals has not been covered as that has been covered by IS : 8899-1978*.

Although the properties of quartz are very stable, the ultimate performance of the element is largely dependent on the way in which it is used. Its performance will largely depend upon the environment and the associated electrical circuits. All users should discuss their particular application with the crystal manufacturer at the earliest stage in any design.

---

*Guide for the use of synthetic quartz crystal.

There are a number of different cuts and modes of vibration which will produce crystal units of near zero temperature coefficients over a wide frequency range.

3.2 Modes of Vibration as a Function of Frequency — The frequency range covered commercially by quartz crystal units may be taken as a few hundered hertz to 200 MHz. Use is made of many cuts and modes of vibration to cover this range and crystals of the common types are summarised in Table 1.

TABLE 1 COMMON TYPES OF CRYSTAL CUTS AND MODES OF VIBRATION

DESIGNATION OF CUT (1)	MODE OF VIBRATION (2)	USUAL FREQUENCY RANGE (3)	APPROXIMATE C_0/C_1 (4)
+5°X Duplex	Flexural	0·2 - 10 kHz	200
XY	Flexural	1 - 50 kHz	600
NT	Flexural	4 - 100 kHz	900
+5°X Bar	Extensional	40 - 200 kHz	130
CT	Face shear	150 - 850 kHz	350
DT	Face shear	100 - 500 kHz	400
SL	Face shear	350 - 700 kHz	400
BT	Thickness shear (fundamental)	3 000 - 30 000 kHz	650
AT	Thickness shear	800 - 5 000 kHz	450-300
	(fundamental)	5 000 - 30 000 kHz	220
AT	Thickness shear 3rd overtone	15 000 - 75 000 kHz	Approx n^2 x 250 where n-order of overtone
	5th overtone	50 000 - 150 000 kHz	
	7th overtone	100 000 - 200 000 kHz	
	9th overtone	150 000 - 200 000 kHz	

NOTE 1 — AT cut crystal units may also be produced in the range 400-800 kHz. The use of AT-cut crystals in this frequency range usually implies using larger enclosures.

NOTE 2 — It should be made clear that a crystal unit produced at any frequency in the above range by a number of manufacturers will differ in many respects. There may be even a difference in cut, but even where this is known to be the same, the equivalent network will almost certainly differ.

NOTE 3 — The choice of mode or cut may be affected by the enclosure size or parameters other than the frequency itself.

NOTE 4 — The C_0/C_1 ratios quoted above are average values. However, various techniques adopted by individual manufacturers in the design of crystal units lead to quite wide variations ; C_0 is the shunt capacitance and C_1 is the motional capacitance.

NOTE 5 — For *AT/BT* cuts the C_0/C_1 ratio will tend to increase with smaller enclosures, particularly at the lower end of the frequency range.

NOTE 6 — Crystals of *AT/BT* cuts are normally termed as HF crystals and others are called as LF crystals.

3.3 Frequency *Versus* Temperature Characteristics — These are, to a first approximation, determined by the temperature coefficients of density, dimensions and elastic modulus of the quartz plate. When the resultant of these three properties becomes zero, the stability of the frequency with respect to temperature will be optimum. A major part of design consists of achieving this optimum condition over a specified range of temperature.

These characteristics will vary considerably with the frequency and mode of vibration used. Typical examples are given in Fig. 2 which shows the form of representative frequency/temperature curves of the cuts on a comparative basis. It is of significance to note that the AT mode is at least an order better than other modes commonly used, once the temperature range specified exceeds 30°C.

These parabolic frequency/temperature curves conform fairly closely to the form:

$$\frac{\triangle f}{f} = a_2 (T_0 - T)^2,$$

where $\frac{\triangle f}{f}$ = the fractional frequency difference, expressed in parts per million (ppm) between temperatures T and T_0,

T_0 = the temperature at which maximum frequency occurs (turnover temperature),

T = any temperature in the operating range, and

a_2 = the constant of the parabola.

Cut	*Value of a_2 (dimension $10^{-9}K^2$)*
BT	40
CT	58
DT	17
SL	17
NT	35
XY	35

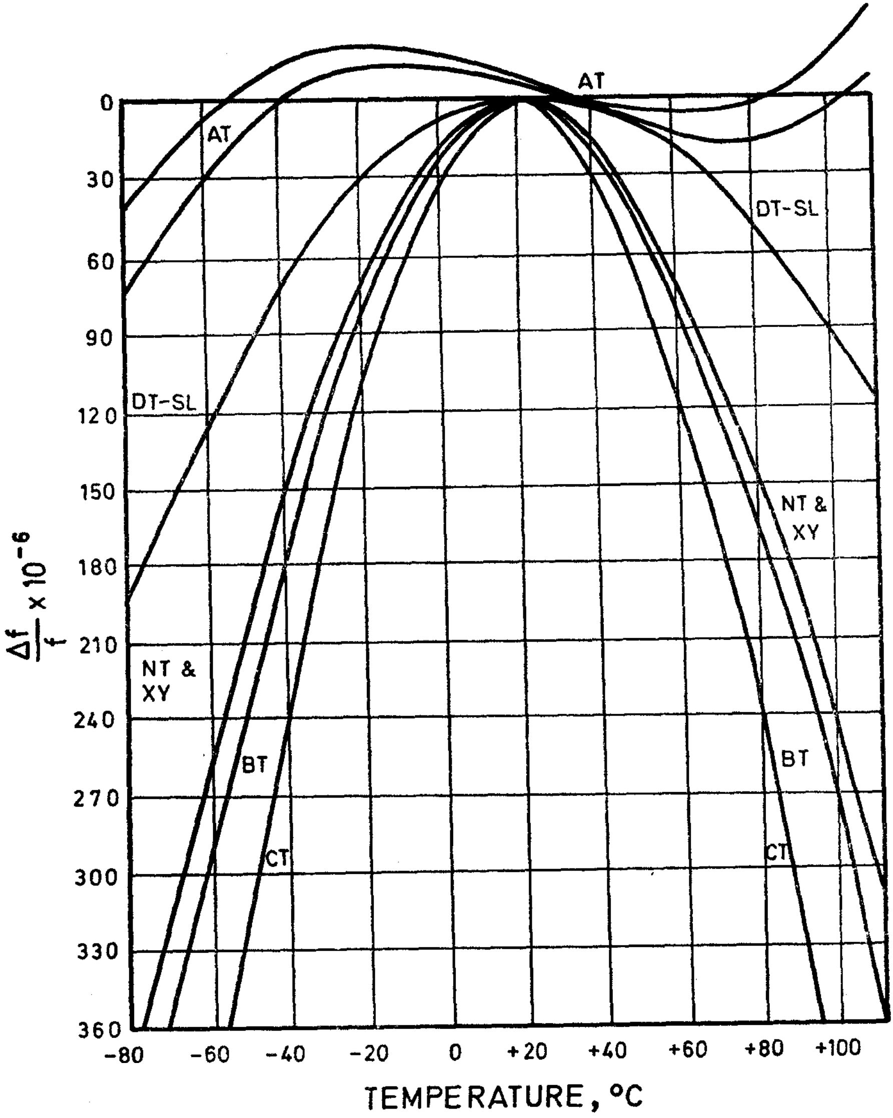


FIG. 2 TYPICAL EXAMPLES

The manufacturer may accept a specification calling for a specific turnover point over a wide range of temperatures. Common values are 25°C and 75°C and he will expect to place the turnover point within ± 10°C, this uncertainty arising from manufacturing tolerances.

In the case of NT-cut and + 5° X-cut units, the manufacturer does not have complete freedom in positioning the parabola and units may differ according to the individual manufacturer's choice of dimensions.

The AT curves shown in Fig. 2 are a restricted range only. A more complete series of curves are shown in Fig. 3. These curves indicate that specific angular ranges may be selected to give a limited performance spread over a particular range of temperatures. However, due to various manufacturing and design limitations, the theoretical curves should be used for guidance only. The manufacturers will advise on the tolerances achievable in practice for the frequencies required.

It may be noted that the 'perfect' crystal, for example, over the temperature range —20 to 70°C, will change 2·5 ppm from the frequency at 25°C.

3.4 Equivalent Electrical Circuit of a Quartz Crystal Unit

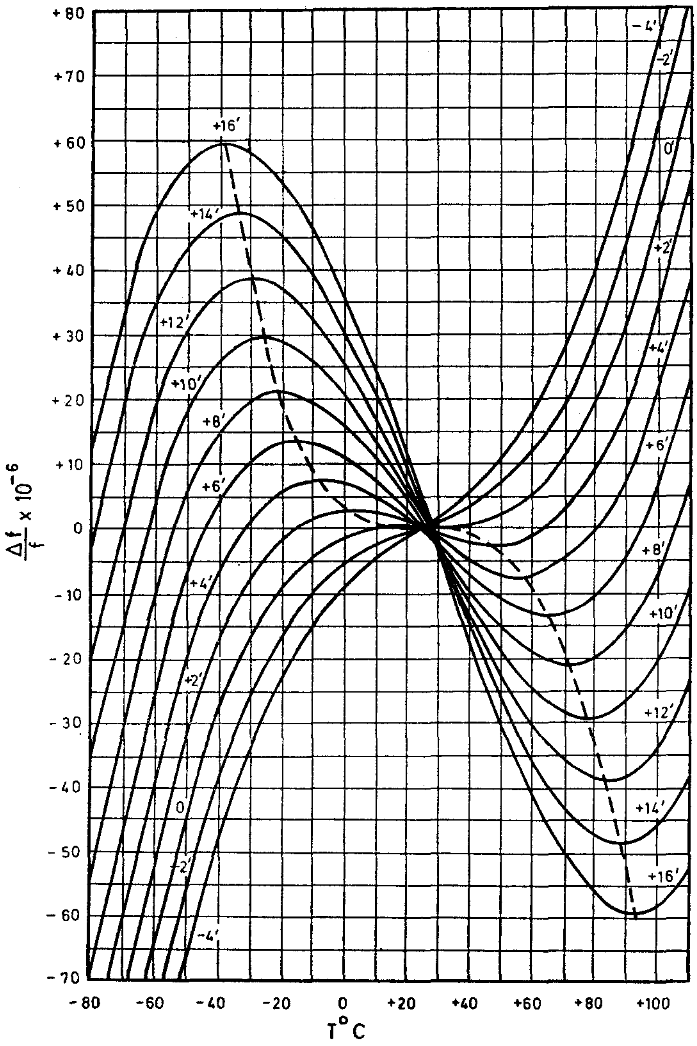
3.4.1 The properties of any mode of a lightly damed mechanical vibrator piezoelectrically excited through electrodes can be represented near a frequency of resonance by an equivalent electrical circuit which consists of a capacitance (C_1), inductance (L_1) and resistance (R_1) in series, shunted by a second capacitance (C_0).

A representation of the crystal unit is shown in Fig. 4.

NOTE 1 — This representation of a crystal unit is useful only of the four parameters are constant and independent on frequency and amplitude. The parameters are independent of frequency if the vibrator has no other mode of motion near the particular resonance. Generally the mode in question is sufficiently isolated from other modes to permit this assumption. When this is not true the equations and measuring methods normally used do not apply. The validity of the circuit representation may be determined by measuring and plotting the impedance or admittance of the vibrator as a function of frequency.

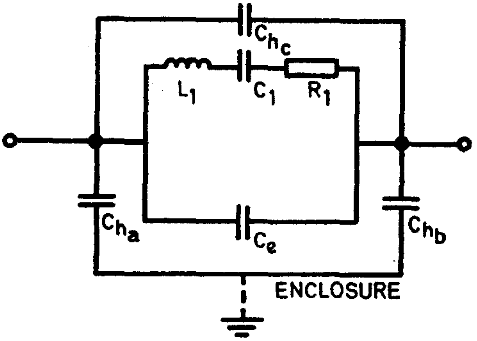
NOTE 2 — It should be noted from Fig. 4 above that the total crystal parallel capacitance is determined by varying conditions of crystals terminations and grounding of the can. It should be borne in mind that with a high impedance circuit the enclosure should be grounded.

NOTE 3 — A commonly used simplified equivalent circuit is shown in Fig. 5.



NOTE — Dotted line represents loci of temperatures at which $\frac{\Delta f}{\Delta T} = 0$.

FIG. 3 FREQUENCY-TEMPERATURE CURVES GENERALIZED AT-CUT



L_1 = Motional inductance (Henry)
C_1 = Motional capacitance (Farad)
C_e = Electrode capacitance (Farad)
C_h = Enclosure capacitance (Farad)
C_o = $C_e + C_h$ effective shunt capacitance (Farad)
R_1 = Motional resistance (Ohm)

FIG. 4 CRYSTAL UNIT EQUIVALENT CIRCUIT

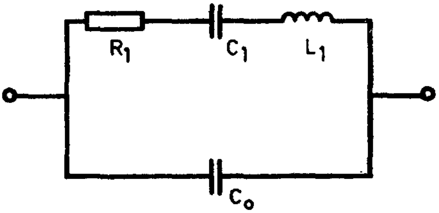


FIG. 5 SIMPLIFIED EQUIVALENT CIRCUIT OF A CRYSTAL UNIT

The inductance is closely associated with the vibrating mass, the series capacitance with the electromechanical coupling of the quartz element, and the resistance with the mechanical inertia of the element mounting system plus acoustical losses to the surrounding environment. The shunt capacitance is made up of the static capacitance between the electrodes, together with the stray capacitance of the mounting system.

There will be two zero-phase frequencies associated with this simple circuit, that at series and that at anti-resonance.

In the case of oscillator crystals they will operate at any frequency within the broken lines of Fig. 6 as determined by the phase maintaining circuit.

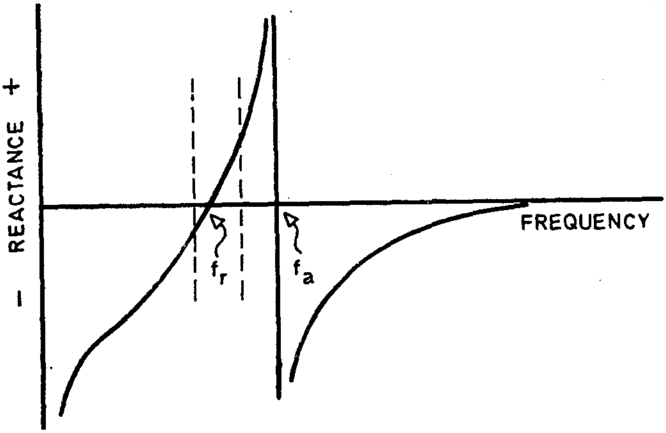


FIG. 6 REACTANCE CURVE

By variation of this reactive condition the crystal frequency may be trimmed to a limited extent.

The degree to which this frequency may be varied (frequency pulling) with respect to different input circuit conditions in determined by:

$$\frac{C_0}{C_1}$$

Nominal values against frequency ranges/modes of vibration are given in Table 1.

In filter application the bandwidth will be affected by this ratio. In general the higher the ratio the smaller will be the bandwidth.

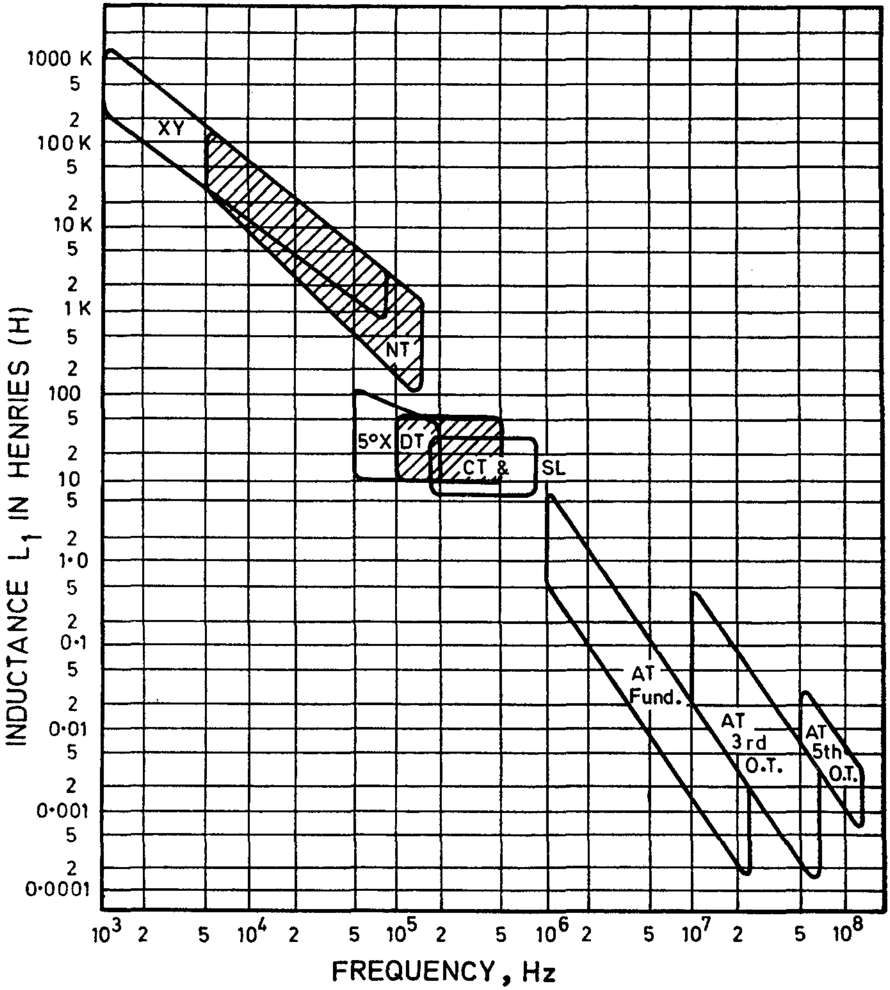
3.4.2 *Detailed Information on Crystal Parameters* — The parameters of the equivalent electrical circuit consist of the motional parameters L_1, C_1, R_1 and the shunt capacitance C_0. All of these are interrelated and a change to one will result in a change in all the others. The only relatively fixed parameter for any crystal of a given construction, cut mounting system and frequency in the maximum 'quality factor' Q and the $\frac{C_0}{C_1}$ ratio. The relationship between these parameters can be seen by the following equations, all of which are commonly accepted approximations used in industry:

$$Q = \frac{WL_1}{R_1}$$

$$W = \frac{1}{\sqrt{L_1C_1}}$$

$$r = \frac{C_0}{C_1} \text{ (usually a constant for a given cut and design)}$$

The following Fig. 7, 8, 9A and 9B give a range of parameters against frequency and cut.



NOTE — The lower values can only be obtained in larger enclosures.

FIG. 7 NORMAL INDUCTANCE RANGES FOR VARIOUS COMMON CUTS VALUES AS HIGH AS 2 OR 3 TIMES THOSE SHOWN MAY BE OBTAINED BY SPECIAL TECHNIQUES FOR UNUSUAL APPLICATIONS

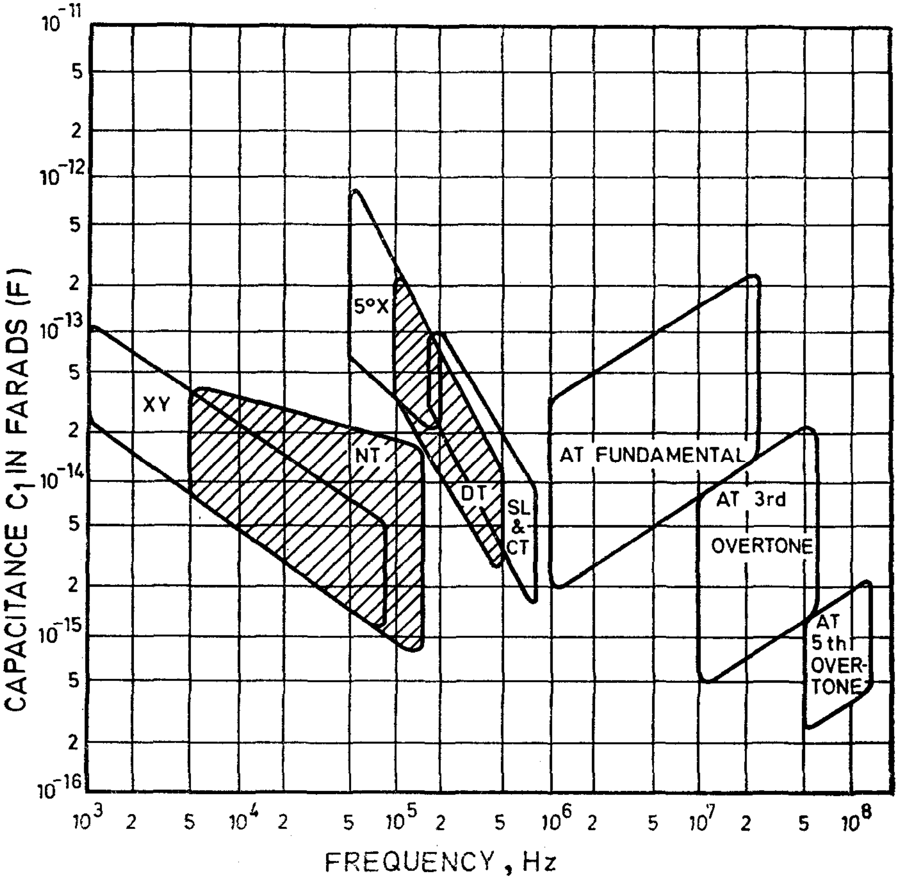
3.4.3 *Crystal Resistance* — The following points on the resistance parameters should be noted, irrespective of frequency:

a) The lowest values are achieved under the evacuated envelopes.

b) The control of resistance by manufacturers is such that a variation of 3 : 1 may be found on any batch.

c) The smaller the enclosure chosen for a given frequency the higher the average value is likely to be.

d) In general with low frequency cuts, their resistance rises appreciably with temperature. For example, CT or DT cuts may have twice the resistance at 85°C that they have at 25°C.



NOTE — The larger values can only be obtained in larger enclosures.

FIG. 8 NORMAL CAPACITANCE RANGE FOR VALUES AS LOW AS 1/2 TO 1/3 THOSE SHOWN MAY BE OBTAINED BY SPECIAL TECHNIQUES FOR UNUSUAL APPLICATIONS

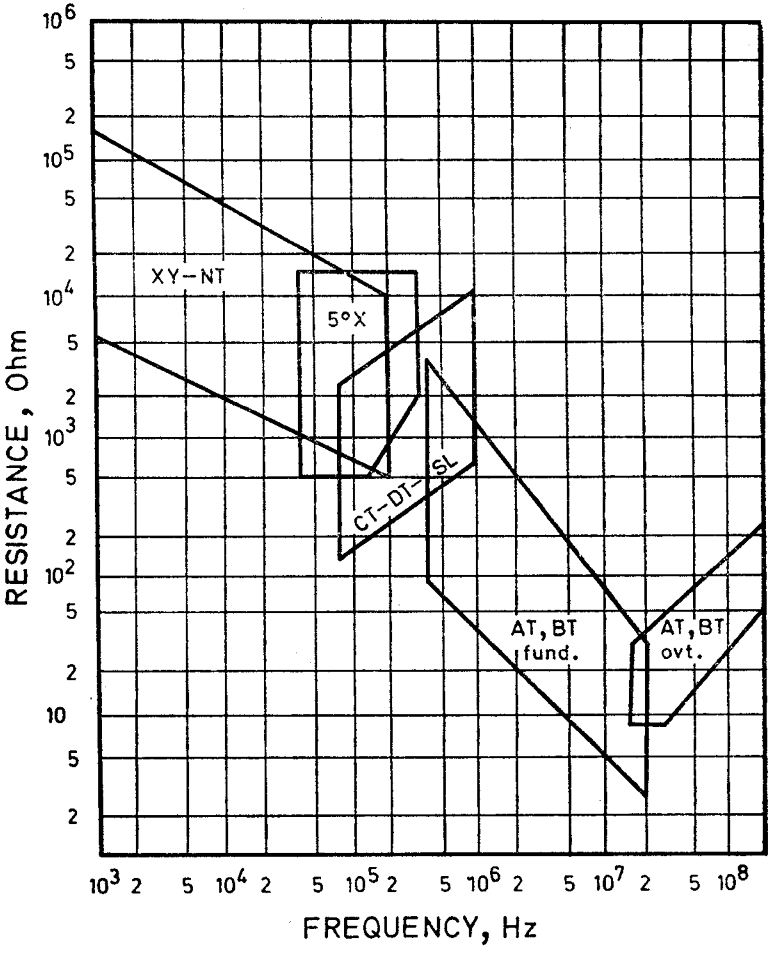


FIG. 9A FREQUENCY CUT AND RESISTANCE RANGE OF HERMETICALLY SEALED CRYSTAL UNITS

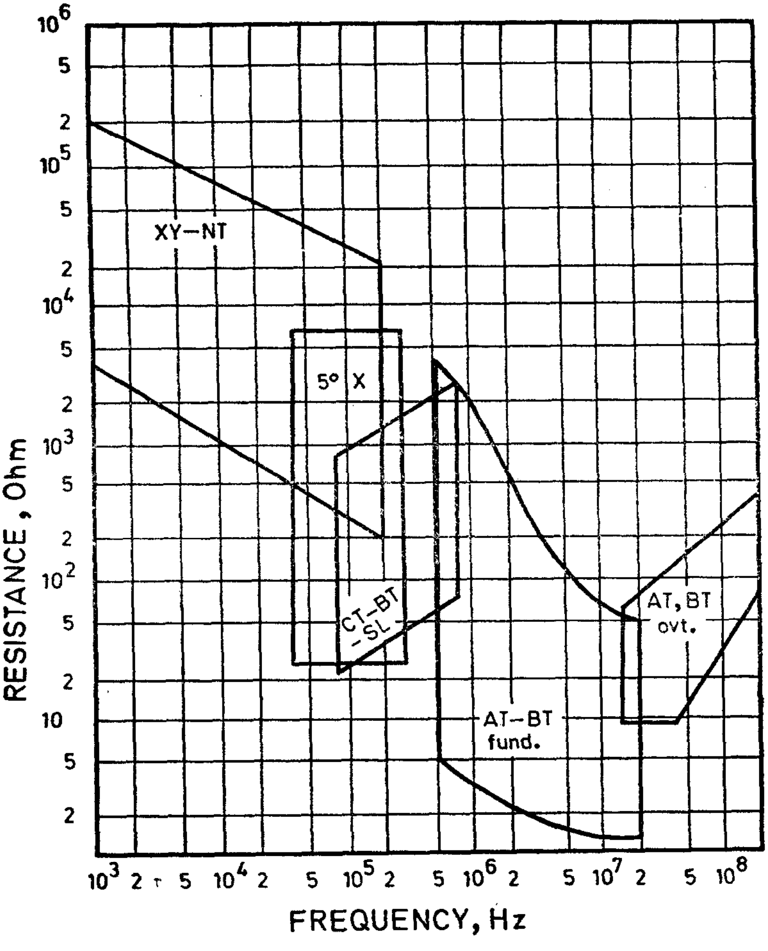


FIG. 9B FREQUENCY CUT AND RESISTANCE RANGE OF EVACUATED CRYSTAL UNITS

3.4.4 *Effects of Drive Level (Power Dissipation and Ratings)* — All crystal units will be found to have their frequency dependent on the drive level. Therefore, the first significant point is to ensure that the drive specified is that actually being used in the equipment.

The effect of drive on the crystal unit is also such that a very high drive could cause an irreversible frequency charge. Therefore, it is essential that the equipment designer ensures that this condition will not be found.

The frequency change with increased drive on AT-cut crystals will be positive and it will be negative on low frequency cuts.

3.4.4.1 *High drive level* — The following summarises the effects of high drive level:

a) Excitation of unwanted modes causing series deformation of the frequency/temperature and resistance/temperature characteristics,
b) Frequency shifts due to crystal heating (usually reversible),
c) Frequency shifts due to overstress (usually irreversible), and
d) Non-linear effects (irreversible).

3.4.4.2 *Low drive level* — At very low drive levels (a few microwatts or less) the resonance resistance of the crystal unit may be much higher than at more normal levels, resulting in oscillator starting problems. Units with similar resistance values at normal drive levels may be aggravated by a period of non-operating storage and is commonly known as second level of drive (SLD).

3.4.5 *Switching, Keying and Modulation* — Some applications require the crystal oscillator to be modulated, or 'keyed' in either frequency or amplitude. Certain limitations must, however, be recognized since quartz crystals have a very high Q (very low decrements). The range of Q to be expected is from 10^4 to 10^6 and it is clear that build-up and decay times for crystal oscillations will be appreciable.

The time required for an oscillator to build up from zero to 99 percent of study amplitude is approximately given by:

$$t = \frac{2 L_1 \log K}{R_N - R_1}$$

where

t = time in ms means millisecond
L_1 = motional inductance in mH,
K = amplitude factor (for example 100 000 mV for an amplitude rise from 10 μV to 100 mV),
R_N = the effective negative resistance of the oscillator circuit in ohms, and
R_1 = resistance in ohms.

3.4.6 *Effects of Ageing* — Quartz crystal units exhibit changes in the resonance frequency and the equivalent resistance as a function of time. These effects are known as ageing. The change of resonance frequency is the greater of the two and is the more important effect in most applications.

The phenomena of ageing is a complex matter involving many factors and, therefore, the subject may only be dealt with in general terms in a document of this nature. For ageing data of a particular type of crystal the manufacturers should be consulted.

Basically all crystal units exhibit frequency ageing which is quasi logarithmic under static conditions. This trend may be disturbed by enclosure leakage, overdrive, severe shock or high temperatures. This ageing will take place whether or not the crystal is being used.

It is generally accepted that glass incapsulated and metal welded units offer the best ageing performance with solder seal metal units being acceptable for many applications. Plastic or unsealed 'crimped' metal holders should only be used in applications where ageing is unimportant.

Factors which contribute to ageing effects, along with graphical illustrations are given below:

a) *Temperature effects* — Maximum irreversible frequency deviation (frequency-ageing) as function of time and temperature is shown in Fig. 10. The absolute value depends on the construction and the enclosure of the crystal unit.

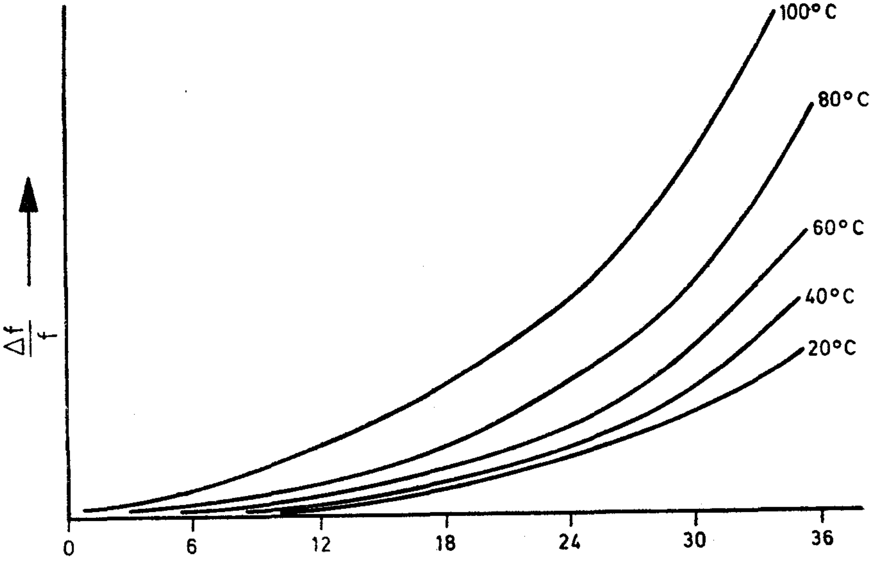


FIG. 10 TEMPERATURE EFFECTS

It should be noted that storage of crystal units with a temperature above the normal operating temperature range may lead to ageing effects which would not occur in normal operation. This is particularly true of low frequency crystal units.

b) *Other effects* — The other effects are shown in Fig. 11

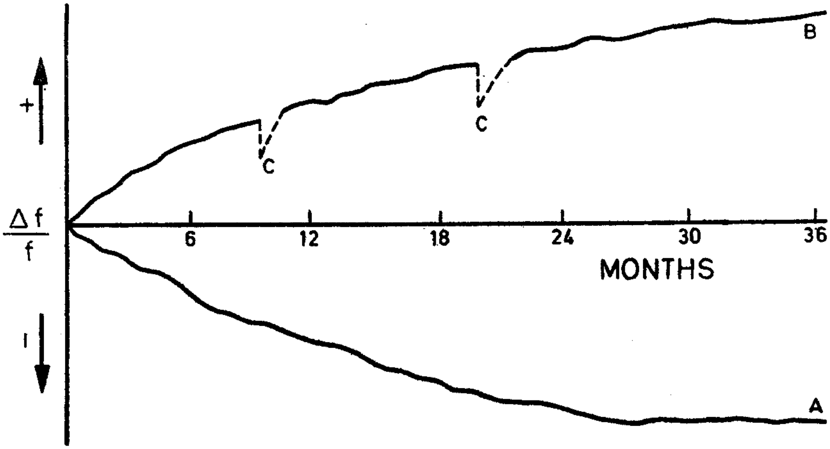


FIG. 11 OTHER EFFECTS

Curve A above the typical frequency ageing caused by contamination. The actual value depends on the changes at temperature and air pressure and also other climatic conditions.

Curve B shows the typical influence of electrode diffusion in the crystal on the frequency. Also recrystallisation of the electrode material may cause the same effect. Sometimes the electrode is stressed when the resonator is vibrating.

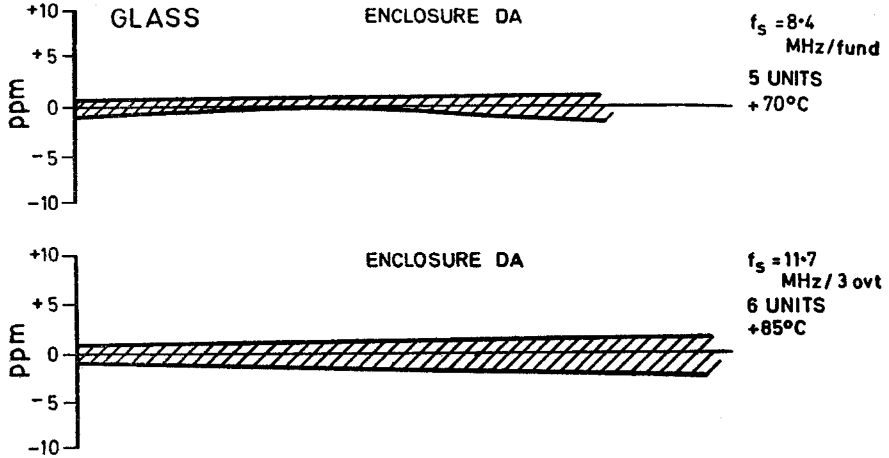
Sub-curves C show the behaviour of the ageing curves due to oscillations being switched off for a short time.

One other factor which relates particularly to low frequency cuts is changes in their mounting structure. When affected by high temperatures the ageing rate may increase to a greater extent than with AT-cuts and under shock greater changes may be found.

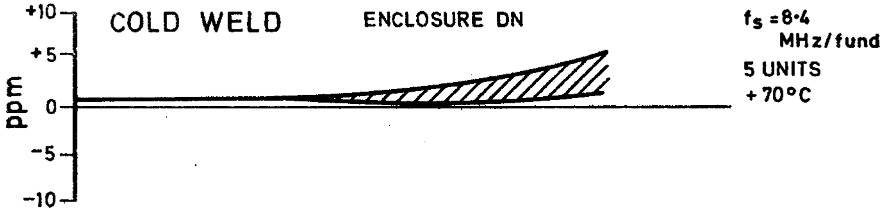
It should additionally be noted that the direction of the frequency change found is such that with AT-cuts it may be either positive or negative whilst with the low frequency cuts it will be positive only.

The measurement of frequency ageing of quartz crystal units needs very careful consideration. The effects of temperature changes, drive level variations, load capacitance changes, etc, shall be considered.

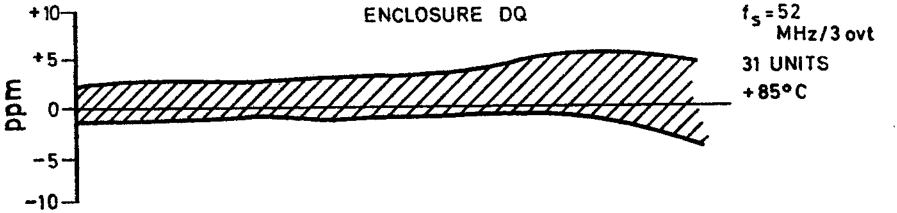
Some measured ageing curves are shown in Fig. 12



12A



12B



12C

FIG. 12 AGEING CURVES — *Contd*

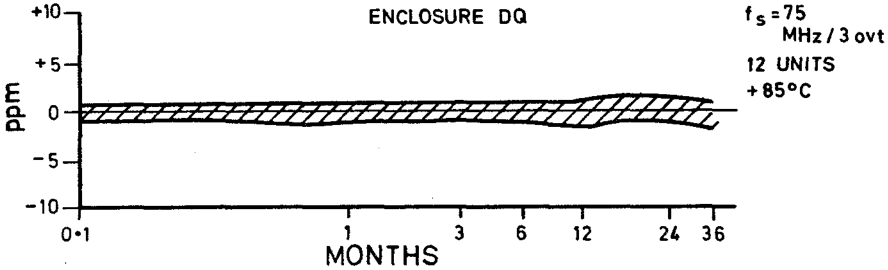


FIG. 12 AGEING CURVES

3.4.7 *Unwanted Responses* — All crystal elements have frequency responses other than the main, or desired, response.

The more obvious ones are the overtones of the main response and, for crystals operating at their overtone by design, other overtones and the fundamental frequency itself.

Generally these responses rarely cause problems, due to loop gain of the oscillator being higher at the design frequency than at other overtones or the fundamental. However, should there be unwanted responses nearer to the main mode and with relatively large amplitude, problems of oscillation at those unwanted frequencies could occur.

Four examples across the frequency range of measured crystal unwanted responses over the spectrum adjacent to the main response, that is, much closer than any of the overtones, are shown in Fig. 13.

These examples reflect the fact that, as the mode of vibration becomes more complex, so do the unwanted response problems.

To a limited extent these unwanted responses can be controlled. This is most feasible at the lower end, longitudinal mode, and most difficult for the thickness shear crystal elements. The techniques for modifying these unwanted response positions and magnitude is based on changes of geometry and plating area. Unfortunately such changes will affect the other parameters C_1, L_1, R_1, etc, and in an extreme case the enclosure size could be a limiting factor. Evacuation of the enclosure increases the unwanted response magnitude. These unwanted responses may also distort the desired response due to temperature and drive changes.

Manufacturer's standard products involve element designs which minimise these effects and, in practice, coupled with reasonable oscillator design, seldom give trouble. However, it should be accepted that there specific C_1 values are imposed or, less directly, where particular frequency pulling clauses are demanded or where high drives are specified, then the unwanted responses could become worse.

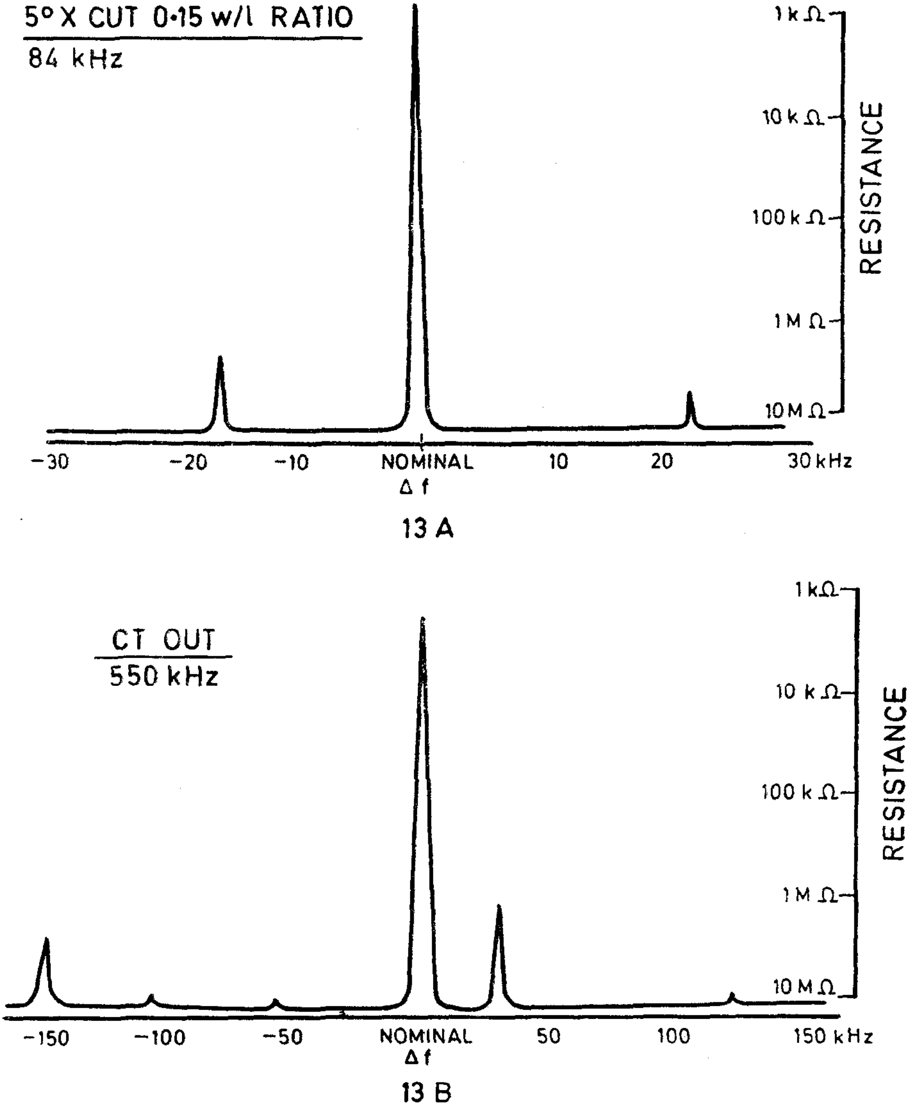


FIG. 13 TYPICAL UNWANTED RESPONSE SPECTRUM — *Contd.*

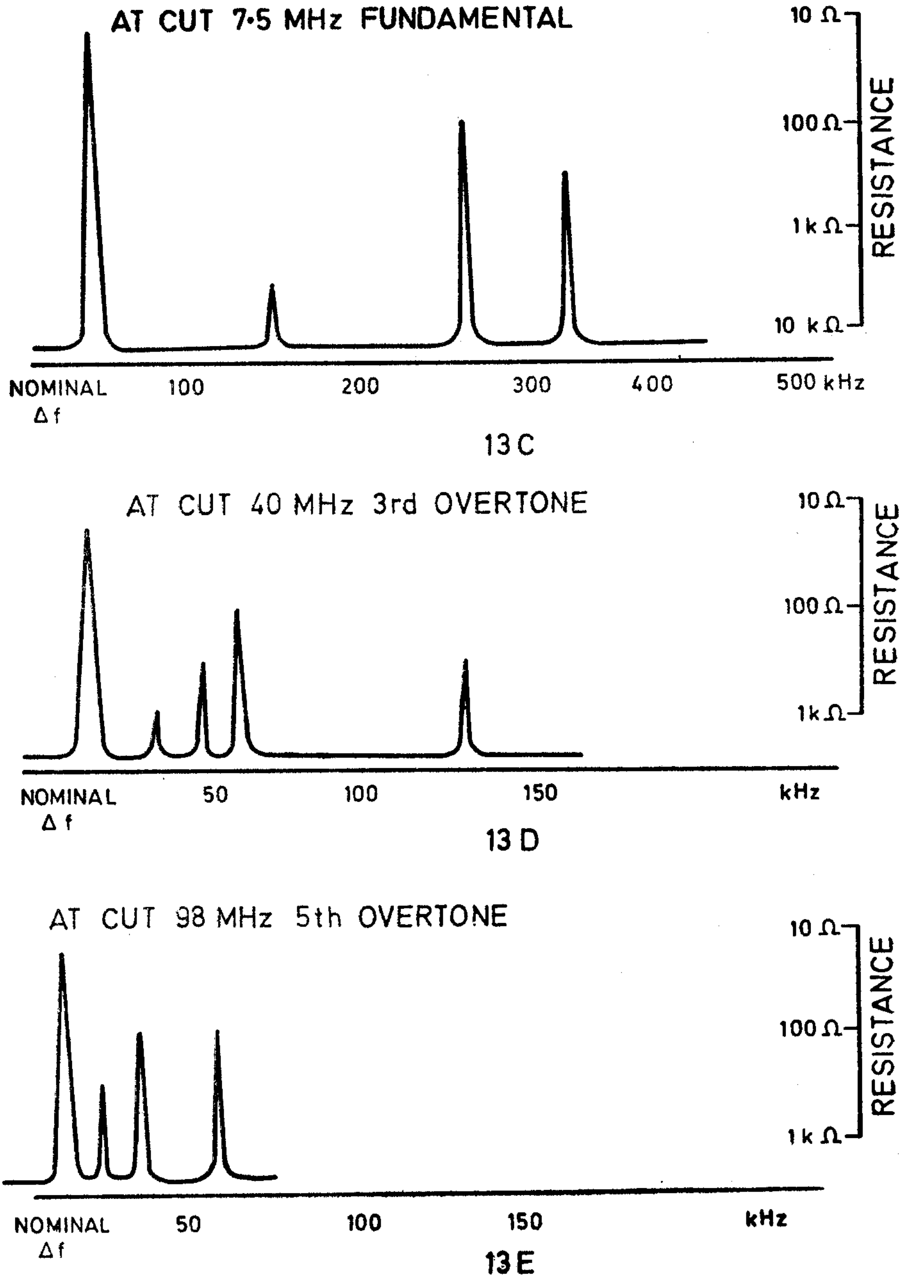


FIG. 13 TYPICAL UNWANTED RESPONSE SPECTRUM

It is common to include a test for unwanted responses. Should it be thoght that there is a possibility of the oscillator triggering off at the unwanted response. Overtone AT out specifications where the unwanted response *will* be relatively close and large in amplitude often include such a test. It is usual to specify over a frequency range about the main response either the ratio of :

$$\frac{\textit{Unwanted response series resistance}}{\text{Main series resistance}}$$

or to specify the minimum resistance that the unwanted response may have in that frequency range.

Finally, in any application where unwanted responses are considered to be a potential problem, crystal manufacturers should be consulted before any attempt to specify the requirement is made. This is essential to ensure that realistic requirements are specified. In this connection it should be realised that any unwanted response requirement is meaningless unless a frequency range over which it applies is specified.

3.4.8 *Mechanical Reliability* — Generally it is found that the most rugged units are the high frequency AT-cuts as they may be mounted quite rigidly without severe effect on their vibrating qualities.

Crystal units with CT, DT, X cuts, etc, are usually less robust as their mounting systems are weaker.

Regardless of the type of unit used, very severe environmental requirements may not be possible without some relaxation of the electrical performance requirements.

It should be remembered that all crystal units exhibit changes in frequency and resistance under physical stress long before they break and therefore when specifying the environment level it is important to give the maximum changes that are acceptable.

Due to crystal unit design limitations it may be necessary for any additional protection against shock and vibration that is required to be built into the equipments crystal fixing arrangements.

Where leads are to be formed it is essential to ensure that the minimum strain is placed on the glass/metal seal. Otherwise they may not remain hermetic.

It is inadvisable to solder on to the metal cans after the sealed unit has been tested.

3.4.9 *Crystal Enclosures* (*Holders*) — These fall into three main categories:

a) Glass,

b) Metal, and

c) Plastics.

The glass units are usually evacuated whilst the metal units are often nitrogen filled.

The glass units for crystals below 600 kHz are usually of ' soft ' lead or soda lime tube construction. Where AT-cut crystals are concerned, they are more often hard borosilicate glass versions of the smaller commonly used metal enclosures.

Metal units increasingly use welded seals which facilitate evacuation and offer better long term hermeticity.

The tendency being for a smaller holders it should be noted that these will turn to decrease the C_1 and also decrease at least the average resistance found. They will also need low drive levels.

NOTE — The plastics enclosures are not generally used for professional purposes.

4. CRYSTAL UNIT AS A CIRCUIT COMPONENT

4.1 General

4.1.1 *Frequency Tolerance and Operating Temperature Range* — Frequently the engineer has tended to specify his frequency requirement at room temperature and to neglect to add the frequency change permissible over the operating temperature range. Since all equipment has to maintain over a temperature range it is necessary to fix these values. In so doing allowance should be made for the equipment heating which may occur.

There are two principal methods of specifying frequency tolerances over the operating temperature range:

a) Specify an overall frequency tolerance over the operating temperature range such as ± 50 ppm from — 55°C to + 90°C. This method is generally used with relatively wide tolerances in applications where frequency trimming is not employed, and

b) Specify ' partial ' tolerances as follows:

    1) Tolerance at reference temperature ± 20 ppm, and

    2) Tolerance over the temperature range —30°C to + 60°C ± 30 ppm referred to the frequency at the reference temperature.

The method given at (b) above is generally used with tighter frequency tolerances where frequency trimming is used to eliminate the frequency tolerance at the reference temperature.

It should be noted that with most low frequency crystal units having parabolic frequency/temperature curves, this method can be used to give improve performance without employing frequency trimming by specifying the tolerance at the reference temperature in the form 0 to + 'X' ppm.

Allowance should also be made for the ageing of the crystal unit.

Reference should be made to the international or national specifications for 'preferred' combinations of temperature range and frequency tolerance or the manufacturer should be consulted.

Where maximum frequency stability is required and power and space are available, controlled temperature operation should be considered.

4.1.2 *Load Capacitance, Frequency Pulling* — In **3.4.2** the electrical characteristics of the units were discussed. In practice the unit is often associated with an external reactance to facilitate pulling out the frequency tolerance that the manufacturer must have. In oscillator applications this reactance should be capacitive and, therefore, only this case is now considered from the frequency and resistance standpoint.

4.1.3 *Effect of Variation of Load Capacitance on Pulling* — In Fig. 14 the crystal is shown with a series connected load capacitance C_L. In this condition the net-work is operated to the minimum impedance condition. It may be shown that:

Formula

$$fL = f_s \left[1 + \frac{C_1}{2(C_0 + C_1)} \right]$$

or

$$\frac{\Delta f}{f_s} = \frac{1}{2} \left[\frac{C_1}{C_0 + C_1} \right]$$

where $\Delta f = f_L = f_s$

This formula applies when at the oscillator terminals the phase shift is zero.

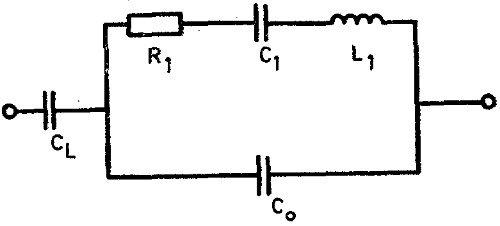


FIG. 14 CRYSTAL WITH SERIES LOAD OF CL

In Fig. 15 the crystal is shown with a parallel connected load capacitance C_L. In this condition the network is operated at maximum impedance condition.

In this case the above formula applies when the phase shift is 180°.

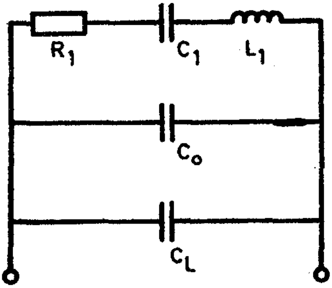


FIG. 15 CRYSTAL UNIT WITH PARALLEL LOAD OF C_L

From these simple equations most calculations and predications of operating frequency may be obtained. It should be noted that in the conditions shown in Fig. 14 the resonance curve of Fig. 6 has been modified by moving the point f_s upwards in frequency with only a small change in the frequeney of f_s. In the conditions of Fig. 15, the point f_s has been moved downwards in frequency with only a small change in the frequency of f_s.

Typical frequency changes to be expected are given in Table 2.

It is very important to define the mean load capacitance to enable the actual crystal frequency to fall within the tolerances placed on the nominal frequency in the specification. It is also important to use, wherever possible, standard values of load capacitance, for example, 10 pF, 20 pF, 30 pF or 50 pF.

It should be noted that a tolerance of $\pm\frac{1}{2}$ pF at 20 pF load capacitance may lead to a frequency error of ± 10 ppm on some crystal elements.

For more general use Fig. 16 illustrates the degree of frequency variation for a given load capacitance change as a function of the capacitance ratio, and nomogram (Fig. 17) shall apply.

TABLE 2 TYPICAL FREQUENCY CHANGES

(*Clause* 4.1.3)

TYPE OF CRYSTAL ELEMENT	FREQUENCY VARIATION PER MILLION PER pF LOAD CAPACITANCE		Δf IN PARTS CHANGE IN NOMINAL			
	Mean 20 pF		Mean 30 pF		Mean 50 pF	
	Δf Min	Δf Max	Δf Min	Δf Max	Δf Min	Δf Max
AT thickness shear fundamental	10	20	4	12	2	5
AT thickness shear 3rd overtone	1·5	2·5	1	1·5	0·3	0·6
5th overtone	2·0	1	0·1	0·5	0·04	0·2
7th overtone			Not practical			
BT thickness shear	6	14	3	8	1	3
CT face shear	4	11	2	6	1	3
DT face shear	5	16	2·5	9	1	4
+ 50 × extensional	20	40	12	30	6	15
NT flexural	Mean 100 pF 9					
XY flexural	14					

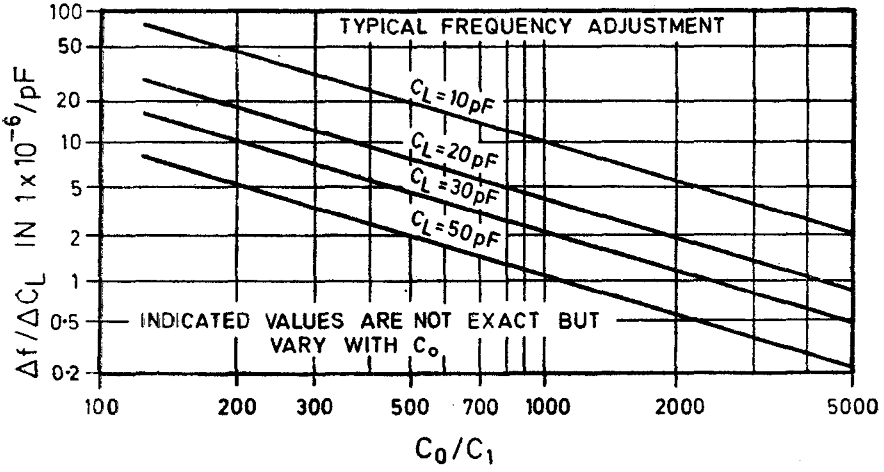


FIG. 16 DEGREE OF FREQUENCY VARIATION OF A GIVEN LOAD CAPACITANCE CHANGE AS FUNCTION OF THE CAPACITANCE RATIO

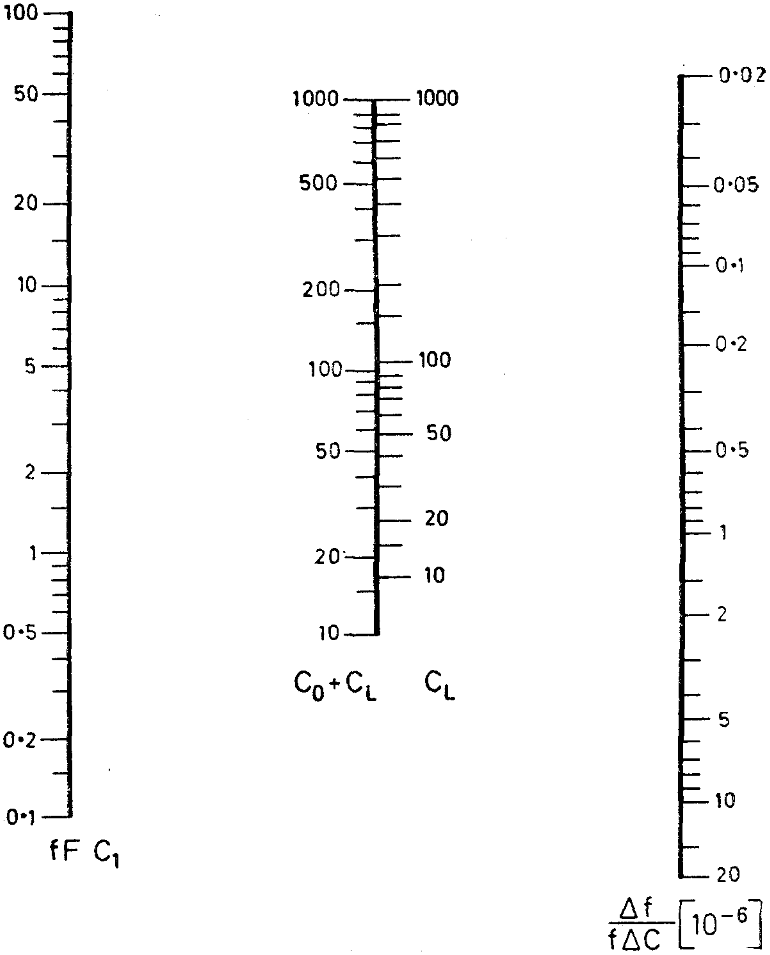


FIG. 17 RATE OF FREQUENCY CHANGE AS A FUNCTION OF LOAD CAPACITANCE (NOMOGRAM)

4.1.4 *Effects of Load Capacitance on Crystal Resistance* — The equivalent circuit of the crystal has one other important parameter, this is R_1, the motional resistance. This factor controls the Q of the crystal and will define the level of oscillation in any maintaining circuit. The load resonance resistance for a given crystal unit depends upon the load capacitance with which that unit is intended to operate; the crystal manufacturer has equipment to measure these quantities.

As was seen earlier, the frequency of oscillation is the same in either a series or parallel connection of the load capacitance. If the external capacitance is designated then the equivalent loss resistance may be calculated as follows:

$$\text{Load resonance resistance} \quad (R_L) = R_1 \left(1 + \frac{C_0}{C_L}\right)^2 \text{ ohm}$$

In most cases, the resistance of a particular unit cannot be predicted during manufacture ; it is only possible to ensure that it is less than the maximum laid down in the specification. In fact, a spread in this parameter of two or three to one is not uncommon in the production of some types of crystals.

Finally it should always be remembered when specifying that the resistance with a series capacitor is always increased over the value of the crystal itself. Some national specifications do give values of resistance with load capacitance as well as without.

4.1.5 *Frequency Pulling Calculation* — Table 2 gives a range of typical frequency pulling capabilities for given modes. An approximation to the pulling for any crystal can be calculated from this simple formula.

$$\frac{\Delta f}{f \, \Delta C_L} \, (10^{-6}/\text{pF}) = \frac{\Delta f}{f_r \, (C_0 + C_L)}$$

where $\Delta f = f_L - f_r$

NOTE — Attention is drawn to the difficulty of pulling crystal units with high C_0/C_1 ratios.

4.1.6 *Trimmability* — The ‘ trimmability ’ method of specifying the crystal units frequency change with capacity characteristics is used generally as a means of ensuring that the units received will all have similar performance. It anticipates the problems of two suppliers providing distinctly different crystals. It is also used to ensure a range frequencies all being of similar trimmability. In this application it is a go/not-go method. A typical requirement might be expressed as ‘the frequency change between series and a load capacitance of 30 pF shall be between 200 and 400 ppm’.

4.2 Basic Concept of Oscillators

4.2.1 *Factors Affecting the Frequency* — In an oscillator whose frequency is to be decided principally by a crystal resonator, it is understood that the circuit and conditions of operation have significant effect on the oscillation frequency.

Although a crystal unit is adjusted during manufacture to a nominal frequency, the conditions under which this frequency is to be obtained in a crystal oscillator shall be adequately defined. The following points shall be considered in order to achieve the desired result.

4.2.2 Types of Oscillators — A crystal controlled oscillator can generally be described as an amplifier with a feedback network containing a crystal resonator. To sustain oscillation, the loop gain shall exceed unity at a frequency at which the total loop phase is $2n\pi$ (n = O or some whole integer).

Crystal controlled oscillators may be divided into two broad groups:

a) Those that may close the phase loop without the crystal. These are generally called series resonance oscillators; and

b) Those that use the crystal as an inductance in a phase shifting feedback network. These should be called positive reactance oscillators. These are commonly called parallel resonance or anti-resonance oscillators. These terms are not technically correct and their use should be avoided. Both groups should be designed to ensure adequate selectivity at the correct frequency.

4.2.3 *Series Resonance Oscillators* — While maximum amplitude and zero phase would coincide with a crystal unit having infinite Q, with practical units they do not. Zero phase is used because it may be more precisely determined. While the difference is not great, it is sufficient to cause changes greater than many required tolerances (*see* Fig. 18).

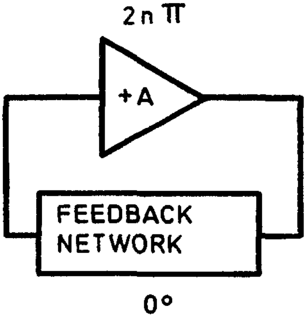


FIG. 18 SERIES RESONANCE OSCILLATORS

4.2.4 *Positive Reactance Oscillators*

a) The basic principle of this type of oscillator is shown in Fig. 19

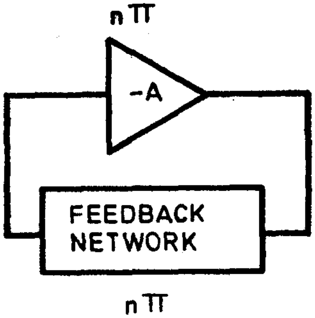
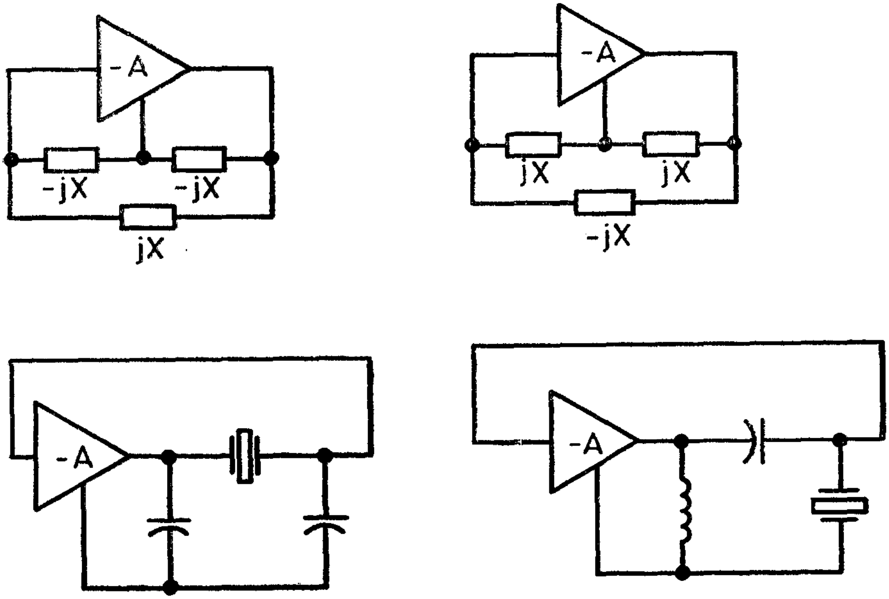


FIG. 19 POSITIVE REACTANCE OSCILLATORS

b) The amplifier in this circuit usually consists of an inverter and the crystal unit operates as an inductance in the phase shifting network required to close the phase loop. For this to occur the conditions of Fig. 20A or 20B must be met.



20 A

20 B

FIG. 20 POSITIVE REACTANCE OSCILLATORS WITH PHASE SHIFTING NETWORK

c) The operating principle of this oscillator is to have the crystal and its associated network provide the necessary phase shift to close the phase loop. The crystal unit then corrects any phase instability with a minimum frequency shift.

d) A series resonance type of oscillator may be operated as a positive reactance oscillator by connecting a capacitor in series with the crystal unit as shown in Fig. 21. In this case the negative reactance of the capacitor plus any incidental reactance are cancelled by the positive reactance of the crystal unit. For this type of operation the crystal units are operated with significant, deliberate phase shift. Therefore, they should be specified for operation with the appropriate load capacitance and *not* for series resonance.

e) In any of the positive reactance circuits, frequency adjustment may be provided by a variable capacitor in the crystal phase shift network.

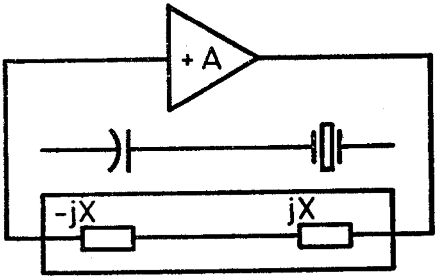


FIG. 21 POSITIVE REACTANCE OSCILLATOR BY CONNECTING CAPACITOR IN SERIES WITH CRYSTAL

4.2.5 *Oscillator Problem*

a) The advent of economical solid state amplifiers, using either discrete or integrated circuits has resulted in another class of oscillators that may present serious problems. Poorly designed multistate circuits can result in phase delays that make the oscillator appear inductive.

b) If the phase error is small, it can be corrected by a capacitor in series with the crystal unit as in Fig. 21. For series resonance operation, the capacitor should be chosen to bring the phase shift to zero.

c) If positive reactance operation of the crystal is desired, the capacitor may have a smaller value. In that case, the value of C_L as seen by the crystal unit will be larger than the capacitor value.

d) If the phase delay is too severe, the capacitance required to correct it becomes so small that the circuit becomes unstable. In some cases the phase loop can be closed by C_0 of the crystal unit, allowing the oscillator to operate with no control by the resonator.

4.3 Oscillators, Practical Considerations

4.3.1 *General* — If an oscillator is to be considered a series resonance type, the phase shift between the crystal terminals shall be small enough to cause the crystal to shift frequency by only a small percentage of the calibration tolerance.

4.3.2 *Crystal Resistance* — It shall be realised that variation in resistance should be allowed for in oscillator design. The highest resistance crystal defined in the specification should operate satisfactorily whilst those of the lowest resistance should not give rise to excessive drive levels. For certainty of starting, the oscillator circuit should be so designed that it will oscillate with crystal units having three times the maximum resistance specified. The necessity for this arises from the fact that the resistance of the crystal units at levels of drive approaching noise level may be greater than the maximum under specified test conditions (*see* **3.4.3**).

4.3.3 *Unwanted Responses* — In practice it is seldom that, when used for oscillator application, these responses give any trouble.

Whether these unwanted responses cause troubles in oscillator applications is a function of both the oscillator and crystal design. Often problems arise when crystals are used in applications involving multiple swithed crystals. It should be noted that grounding of the crystal enclosures and shorting out of the crystals not connecting into the circuit can considerably reduce the possibility of oscillation on unwanted frequencies.

It should be realised that certain crystal units exhibit unwanted responses which are predictable and well known to the crystal manufacturer. Examples of these are the extension modes of flexure.

The most obvious cases that shall not be neglected are the extension modes of flexures and face shear mode crystal units, the fundamental of overtone units, and in harmonics of contoured AT crystal units.

In the case of precision oscillators, such as a TCXO, the presence of very weak coupled modes may cause ripples in the performance characteristic. These aspects should be referred to the manufacturer.

When it does become necessary to reduce their amplitude it usually results in an increase in the resistance of the main response.

Testing for unwanted responses may be very expensive and it is fortunate therefore that for oscillator application it is usually adequate to test these as part of the initial design assessment only.

4.3.4 *Drive Level* — It is recommended that oscillator circuits have a high loop gain at start and then remain low thereafter. This is particularly important where the drive level is very low to ensure crystals start up quickly. The equipments actual drive level should always be specified.

4.4 Frequency Stability — The frequency stability of a quartz crystal oscillator depends principally upon the correction of oscillator phase error that is provided by the crystal resonator.

For a given oscillator, short term stability is primarily a function of the loaded Q and C_0/C_1 ratio of the crystal resonator, as well as of environmental factors such as temperature and shock. Long term stability is principally a function of ageing of the crystal unit.

4.5 Use in Filter Applications — Quartz crystal units used as filter elements are basically the same as crystal units for oscillator application and are subject to similar design and manufacturing techniques. There are specially design monolothic units but these may be considered as filters. Information on these will be found elsewhere.

However, because of the different requirements of the applications the relative importance of certain aspects of the crystal specification differ.

For oscillator crystals, the frequency tolerances at the reference temperature over the operating temperature range and as a function of time are usually the most important.

With crystals for use in filter applications these parameters are also important, but perhaps more important are the values and tolerances of the crystal equivalent circuit elements and the position and magnitude of unwanted responses.

The clauses of this document dealing with these subjects give some information about these factors but, in general, all applications for crystals for use as filter elements require close consultation with the crystal manufacturer.

Whilst crystals for oscillator application may often be chosen from standard lists contained in crystal manufacturers catalogues, crystals for filter application shall be discussed with the manufacturers before a mutually statisfactory specification can be achieved.

5. FACTORS AFFECTING COST AND AVAILABILITY OF QUARTZ CRYSTAL UNITS

5.1 General — Almost all factors concerning the specification for quartz crystals affect their cost and availability. Consideration of all the factors dealt with in this document are necessary, therefore, to arrive at a specification for a crystal unit which will perform its function satisfactorily and be obtainable at the lowest cost with maximum availability. By availability is meant the ability to obtain crystals from more than one source within a reasonable period.

The information in this section, is, therefore, limited to the main factors affecting cost and availability, but it is re-emphasised that all aspects concerning the crystal specification can have an effect on these factors. Because many quartz crystals are custom-made devices, it is impossible for the crystal manufacturer to carry a stock of finished crystals. Each order for crystals of this type therefore, is treated by the manufacturer individually and he has to make an allowance for the anticipated losses during the production cycle. If the manufacturer's assessment is correct, the ordered crystals should be delivered on the promised date. If not, a re-order has to be placed and this invariably gives rise to late delivery.

Thus the specification for a quartz crystal affects the cost and availability of the units.

5.2 Crystal Frequency — Often the choice of the frequency of the crystal to be used in any application is negotiable at the design stage. The designer should realise that the choice of crystal frequencies at or near the limits (high or low frequency) for any cut or enclosure style will probably lead to penalties in terms of cost and availability. If the frequency is negotiable, crystal manufacturers should be consulted before a final decision is made.

5.3 Crystal Enclosures (Holders) — The size of the crystal enclosure determines the maximum size of the resonator that it may accommodate. This limits the lower end of the frequency range for each enclosure style. It may also limit the ruggedness, reproducibility, and choice of equivalent circuit parameters. It can also significantly increase the cost. Caution shall be used, therefore, when approaching the lower frequency limit for a given enclosure and the crystal manufacturer should be consulted while alternatives can still be considered.

5.4 Ferquency Tolerances — In general, frequency tolerances and the operating temperature range over which they apply should be determined from a knowledge of the system requirements.

Where the same equipment is destined for different territories with difference climatic conditions and specifications, consideration should be given to having a number of different crystal specifications to cover these different requirements instead of standardising on the most difficult specification.

5.5 AT-Cut, Temperature Coefficient Cost Aspects — A guide to the penalties of specifying increasingly smaller frequency variations with temperature for AT-cut crystals are high-lighted in Fig. 22.

It will be seen that the cost rises sharply when approaching the curve of zero cut angle tolerance and it should also be noted that this is based on theoretical condition. The practical state of the art condition will appreciable increase the cost aspect.

5.6 Ageing — This characteristic probably offers the largest cost and availability possibilities.

It is normal to specify an ageing 'level' for the product without it being a specific test condition. It is understood that this 'level' will be under continuous surveillance by the manufacturer by systematic sampling of the overall product. It is accepted that some units may be worse than the figure quoted. This is covered by the standard cost of the product.

To ensure that essentially all the units received are better than a specified limit usually means that the manufacturer is measuring every device and selecting them.

Apart from the cost of this the time scale is considerable and delivery agreements are more difficult to maintain. The most expensive specification adds the additional requirement that after this ageing period each crystal shall also be inside a frequeney tolerance with respect to nominal frequency.

Most careful thought, therefore, shall be given to the ageing problems and one useful exercise for the more common application crystals is to consider the statistical possibilities of the extreme tolerances of setting up to nominal, temperature effect and ageing coinciding on one unit.

The best solutions to ageing may only be obtained by close liaison between the customer and the manufacturer.

5.7 Environmental — It is generally accepted as being minimum reference level which adequately covers most usual applications. Additional or

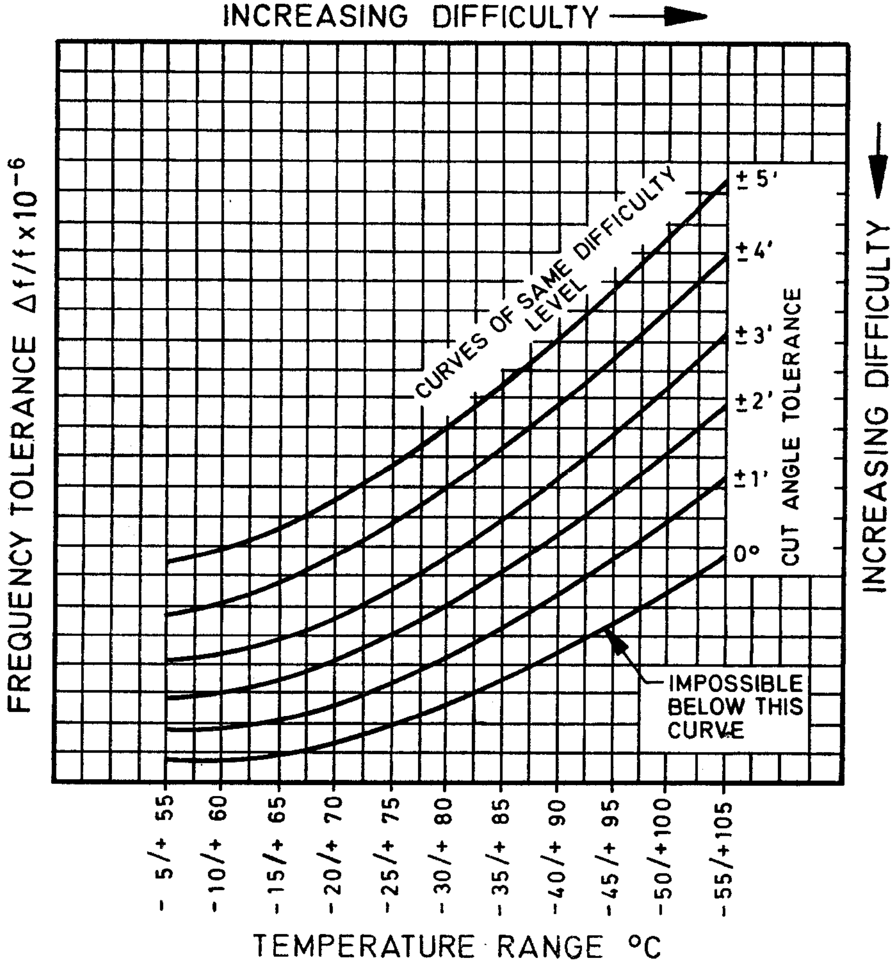


FIG. 22 AT-CUT CRYSTALS — TEMPERATURE BAND/FREQUENCY TOLERANCE DIFFICULTY ASPECT

special tests may be expensive to attain as in the simplest case the manufacturer may not have access to the testing equipment or in other cases may need to design special "non-standard" units. A long look at this problem by the user is worthwhile for it may be more economical for him to subsidise the capability of the standard crystal in his equipment than purchase a special crystal, particularly if he requires to always have a second source of supply.

It should also be borne in mind that when subjected to a series of different environmental conditions the crystal frequency and resistance will change a little. These changes for each condition may not be cumulative but the changes specified may be critical to the availability of the crystal.

5.8 General Testing Considerations — The cost and time of testing may be very high and therefore consideration should be given to the application of statistical sampling. Careful thought on the important of each of the parameters should be given by assessing whether they may be considered as 'Critical', 'Major' or 'Minor' for any particular requirement.

Details of standard test methods are covered in IS : 8271-1976*.

Generally these will be used automatically and, therefore, it is advisable to consider these carefully in case they are not applicable for a particular requirement. They could be technically inadequate or unnecessarily expensive.

Use of 'preferred' test conditions is the least expensive basis for a specification as the manufacturer will have sophisticated standard equipment to cover these. The most expensive action is to supply 'special' equipment and methods. It is particularly true if it is the maintaining oscillator which will never be compatible with the manufacturers standard system either mechanically or calibration-wise.

6. TECHNICAL DATA TO ACCOMPANY ORDER FORM

6.1 Commercial Catalogue — Where requirements may be met by a standard item chosen from the commercial catalogue of a quartz crystal manufacturer, it is sufficient to specify the frequencies and the catalogue reference. Where this is not so, the requirements given in **6.2** and **6.3** should be referred to. While using these requirements, it should be borne in mind that in addition to the fixing of limits to the chosen parameters it is necessary to include the severity of the testing required, that is, how often the test should be effected, the percentage to be tested and the acceptable failure rate.

6.2 Mandatory Requirements

a) Nominal frequency, frequencies or range of frequencies covered by the specification.

b) Overtone order (or fundamental).

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*Specification for general requirements and tests for quartz crystal units used for frequency control and selection.

c) Operating circuit condition
    1) Load capacitance (if applicable)
    2) Crystal enclosure grounded or not (grounding is recommended).

d) Maximum resonance resistance R or maximum load resonance resistance R_L over the operating temperature range.

e) Overall frequency tolerance over the operating temperature range (state operating temperature range) or partial tolerances.

f) Frequency tolerance at the reference temperature (state reference temperature).

g) Maximum frequency deviation over the operating temperature range with respect to the frequency at reference temperature.

NOTE 1 — The applicable tolerances shall be selected as required.

NOTE 2 — Where special requirements demand that the frequency/temperature characteristic be defined it shall be mutually agreed between the manufacturer and user.

h) Marking.

6.3 Optional Requirements

6.3.1 Electrical Requirements

a) Motional capacitance (C_1)
b) Motional inductance (L_1)
c) Parallel capacitance (C_0)
d) Capacitance ratio (C_0/C_1)
e) Trimmability
f) Minimum quality factor, Q
g) Minimum resonance resistance of unwanted responses over a specified frequency range
h) Maximum resonance resistance or maximum load resonance resistance at a specified reduced level of drive
j) Ageing test ;
Give
    1) Duration and conditions of test
    2) Test temperature

k) Leak rate

m) Insulation resistance;
    1) Measurement intervals
    2) Permissible change in frequency and or resistance

n) Permissible deviation in frequency from a smooth function over the operating temperature range

p) Permissible deviation of resistance from a smooth function over the operating temperature range

q) Operable temperature range

r) Storage temperature range

6.3.2 Environmental Requirements — *See* IS : 9000 (Part I)-1977* for the environmental catagories.

a) Climatic:
    1) Dry heat
    2) Damp heat, first cycle
    3) Cold
    4) Low air-pressure
    5) Damp heat, remaining cycles

b) Thermal shock

c) Damp heat, long term exposure

6.4 Mechanical Requirements

a) Vibration
b) Acceleration
c) Shock
d) Bump
e) Robustness of terminations
f) Soldering

6.5 Additional Requirements

a) Crystal cut

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*Basic environmental testing procedures for electronic and electrical items: Part I General.

INTERNATIONAL SYSTEM OF UNITS (SI UNITS)

Base Units

Quantity	*Unit*	*Symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

Supplementary Units

Quantity	*Unit*	*Symbol*
Plane angle	radian	rad
Solid angle	steradian	sr

Derived Units

Quantity	*Unit*	*Symbol*	*Definition*
Force	newton	N	1 N = 1 kg.m/s^2
Energy	joule	J	1 J = 1 N.m
Power	watt	W	1 W = 1 J/s
Flux	weber	Wb	1 Wb = 1 V.s
Flux density	tesla	T	1 T = 1 Wb/m^2
Frequency	hertz	Hz	1 Hz = 1 c/s (s^{-1})
Electric conductance	siemens	S	1 S = 1 A/V
Electromotive force	volt	V	1 V = 1 W/A
Pressure, stress	pascal	Pa	1 Pa = 1 N/m^2

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'F' Block, Unity Bldg, Narasimharaja Square	BANGALORE 560002	2 76 49
Gangotri Complex, Bhadbhada Road, T.T. Nagar	BHOPAL 462003	6 27 16
22E Kalpana Area	BHUBANESHWAR 751014	5 36 27
Ahimsa Bldg, SCO 82-83, Sector 17C	CHANDIGARH 160017	2 83 20
5-8-56C L. N. Gupta Marg	HYDERABAD 500001	22 10 83
D-277 Todarmal Marg, Banipark	JAIPUR 302006	6 98 32
117/418B Sarvodaya Nagar	KANPUR 208005	8 12 72
Patliputra Industrial Estate	PATNA 800013	6 28 08
Hantex Bldg (2nd Floor), Rly Station Road	TRIVANDRUM 695001	32 27

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